Architectural Prospects for Lunar Mission Support

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Abstract. A top-level architectural approach facilitates the provision of communications and navigation support services to the anticipated lunar mission set. Following the principles of systems architecting (i.e., form follows function) the first step is to define the functions or services to be provided, both in terms of character and degree. These will include communication (telemetry and command) as well as tracking and navigation services. Required performance levels are derived from analysis of the lunar mission model. Consideration of the special needs of robotic and human mission support is appropriate, as is the evolution of the service provision system to the eventual human exploration of Mars. Architectural forms are those physical assets, both hardware and software, that are used to enable the functions to be performed and the services to be delivered. These may include ground stations, lunar relay satellites, Earth-orbiting satellites, optical communications assets, and allocated spectrum.

INTRODUCTION

The U.S. Vision for Space Exploration (NASA, 2004) calls for NASA to achieve a robotic return to the Moon no later than 2008. NASA has responded with plans to launch the Lunar Reconnaissance Orbiter (LRO) in 2008 and follow-on robotic missions (e.g., a lunar lander) in the 2009–2010 time frame. These missions will set the stage for a human mission to the moon as early as 2018, to be followed by sustained human and robotic exploration of the moon and, eventually, Mars. This paper describes an architectural approach that enables design, implementation, and operation of communications and navigation support services for lunar missions. Systems architecting principles are invoked (i.e., form follows function). The first step is definition of the functions or services to be provided, both in terms of character and degree. These include communication (telemetry and command) as well as tracking and navigation services. Required performance levels are derived from analysis of the lunar mission model. Specialized needs of robotic and human missions are considered as well as the evolution of the service provision system to the eventual human exploration of Mars.

Architectural forms comprise physical assets, both hardware and software, that are used to enable the functions to be performed and the services to be delivered. These may include ground stations with monolithic or arrayed antennas that are either commercial or government owned, lunar relay satellites, Earth-orbiting satellites (e.g., TDRSS or GPS), optical communications assets, and allocated spectrum. Next, a first cut at the interfaces between and among the physical forms is examined. Appropriate selection of interfaces enables the services to be provided to customers in a reliable and efficient manner. Germane to this area are routing and networking concepts, as well as operability and interoperability. The paper reviews the relevant services vis-à-vis the hypothesized requirements. Special attention is given to the 2008 Lunar Reconnaissance Orbiter, managed by NASA's Goddard Space Flight Center, as it is the nearest-term mission and the one for which requirements are most defined. LRO may carry a relay radio to support near-term lunar landers. As such, an LRO relay would constitute the first installment of a future lunar network. The paper next presents the candidate architectural forms being considered to meet the requirements for service provision, identifying the various pros and cons of each. An updated status report of current NASA planning in this area will be provided. Finally, it is noted that the large number of international lunar missions expected in the next few years will offer unique communications challenges as well as opportunities. Challenges include sharing limited spectrum. Opportunities include cross-support, such as making use of relay radios on lunar orbiters to support landers. International communication collaborations have proven very useful on Mars. This paper suggests how agencies planning lunar missions could create an international lunar network for the benefit of all.

MISSION MODEL OVERVIEW

It is worth noting that humanity's current effort to explore the Moon has already begun in earnest with a visit to our celestial neighbor by the European Space Agency's SMART-1 Mission (Foing et al., 2003). This ion-drive propelled mission launched in September 2003, arrived in the lunar vicinity in November 2004, and achieved it's science orbit in January 2005. It is currently conducting remote sensing operations.

The Japanese Space Agency, JAXA, plans to launch the SELENE Mission aboard an H-IIA rocket in the 2006–2007 time frame (Sasaki et al., 2003), (Takano et al., 2005). This mission will be the largest lunar mission since NASA's Apollo program. Mission objectives are to understand the Moon's origin and evolution, and to survey lunar resources. SELENE will investigate the entire Moon in order to obtain information on its elemental and mineralogical composition, its geography, its surface and sub-surface structure, the remnant of its magnetic field, and its gravity field. Data obtained will lead to utilization of the moon for human endeavors. The SELENE mission comprises a Main Orbiter and two small satellites. The Main Orbiter will reach the vicinity of the Moon five days after launch, where it will be placed into a peripolar orbit at an altitude of 100 km for a one-year mission. A Relay Satellite will be placed in an elliptic orbit at an apogee of 2400 km, for communications relay between the Main Orbiter and ground station. Finally, the third satellite will assist in measurement of the Moon's global gravitational field.

China has put forth its own plans for exploration of the Moon (Ouyang et al., 2003). The initial project will be to send a remote sensing orbiter to the Moon, named Chang'e-1, sometime during 2007. The duration of this mission is expected to be 12 months. This will be followed by a lander mission, very likely with a rover, sometime in the 2005 –2012 time frame. A third phase, in the 2010–2017 time frame, is likely to witness a sample return mission.

The Indian Space Agency, ISRO, plans to launch the Chandrayaan-1 Mission during 2007–2008 on board India's Polar Satellite Launch Vehicle (Bhandari et al., 2003). This 525-kg satellite will be placed in a 100-km polar orbit around the Moon and it will have a lifetime of two years. Primary scientific objectives for Chandrayaan-1 include terrain mapping, hyper-spectral imaging, lunar laser ranging, and high-energy X-ray spectrometry. Collaborative investigations with ESA will add low-energy X-ray spectrometry, infrared spectrometry, as well as measurement of volatiles and surface magnetic field anomalies. Finally, an Impact Probe has been included in the mission for proving technological elements required for future landing missions.

NASA's lunar exploration efforts commence with the Lunar Reconnaissance Orbiter (LRO) Mission, which will launch in 2008 (Soloff, 2004). Figure 1 shows an engineering view of the LRO spacecraft. LRO's mission is to obtain high-resolution topographical maps of the lunar surface, verify lunar gravity models, and obtain information about resource concentrations of interest to follow-on lander missions. The NASA program is still defining the follow-on missions to LRO. However, it is very likely that there will be one or more lunar lander and/or rover missions beginning in the 2009–2010 time frame and continuing up until the time of human return to the Moon. The primary target for these lander/rover missions is likely to be the lunar south polar region, though other locales cannot yet be ruled out.

NASA now envisions the first human lunar return mission in 2018, with a minimum of two lunar missions per year (Cabbage, 2005). Again the most likely site is the lunar south polar region. The outpost would comprise living quarters, power plants, and communications and navigation systems. A notional polar base is shown in Figure 2. From this base of operations, astronauts would conduct sorties by rover to search for valuable commodities such as volatiles from which water, breathable air, and propellants can be extracted. A key element of the lunar transportation infrastructure will be the Crew Exploration Vehicle (CEV). This vehicle is now planned for initial operation in 2011, one year after the planned retirement of the Space Shuttle Orbiter fleet. The CEV will initially carry three astronauts to the International Space Station (ISS) and launch atop a modified Shuttle Solid Rocket Motor (SRM). A second stage would be powered by a Space Shuttle Main Engine (SSME). The CEV will later be expanded to carry four astronauts to the Moon or perhaps six to Mars. Similar to Apollo-era hardware, the CEV will be mated to a Service Module that will provide power and propulsion to and from the Moon. The Service Module would be jettisoned prior to Earth reentry. The ballistic entry would ultimately result in a landing possibly at Edwards Air Force Base in California, the Carson Flats area of Nevada, or near Moses Lake in eastern Washington state. For its lunar application, the CEV, much like Apollo, will also be mated to a lander that will have a four-legged descent stage, plus a detachable ascent stage. The ascent stage will use liquid methane as fuel. Because it may be possible to produce methane on Mars, this approach will prove out techniques needed for a Mars exploration architecture based on in-situ propellant production (ISPP). Besides the CEV, a heavy lift launch vehicle will be needed to launch the actual lunar lander and the Earth Departure Stage. The CEV and Service Module, which launch on the modified Shuttle SRM stack, will rendezvous and dock in Earth orbit with the payload elements from the heavy lifter. It is evident that the many elements of the lunar transportation system will all have significant requirements for communications and navigation services.

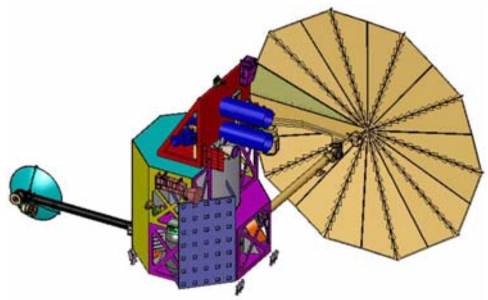

FIGURE 1. Lunar Reconnaissance Orbiter

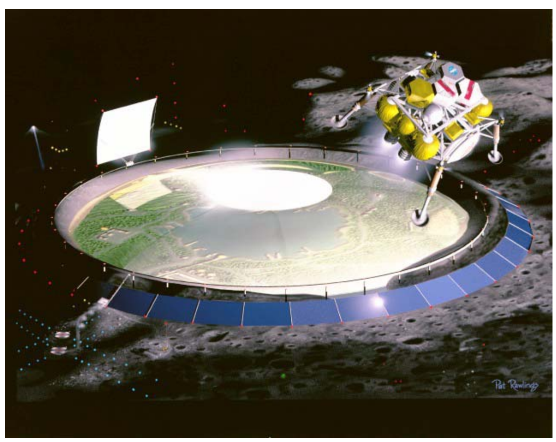

FIGURE 2. Lunar Base

In addition to the missions described above, which are all funded by government entities, there have been a number of proposed lunar missions that rely on private financing. In this venue, it is certainly appropriate to mention the International Lunar Observatory (Friedman and Benson, 2003). This activity is supported by Space Age Publishing Company, along with its subsidiary, Lunar Enterprise Corporation and contractor, SpaceDev. This observatory would conduct robotic radio astronomy from the lunar surface, most likely near the south pole. It would launch from the Baikonur Cosmodrome on a Ukrainian Dnepr rocket, arrive at the Moon in a week to a few months depending upon trajectory selection, land, and begin operations. The landed facility would comprise a multi-wavelength 2-m dish, approximately 3 m in height, with systems to provide communications and solar power.

Finally, an exciting governmental-commercial prospect, named Deep Space Expeditions-Alpha (DSE-Alpha), has only very recently been announced. This partnership would comprise the Federal Space Agency of the Russian Federation (FSA), the Rocket and Space Corporation Energia (RSC Energia) and Space Adventures, Ltd. The first mission envisioned by this consortium, which could launch as early as 2008, would utilize a Soyuz spacecraft to send a crew of three—one cosmonaut plus two paying passengers—to the lunar farside. The mission would involve a rendezvous and docking with an Earth departure stage in low Earth orbit, and possibly a stopover at the International Space Station. Total mission time would be 9 to 21 days. Follow-on missions might be even more ambitious, possibly including a trip all the way to the lunar surface.

ARCHITECTURAL FUNCTIONS AND SERVICES

The lunar missions described above will require certain services in order for them to be technically successful and to accomplish their programmatic objectives. At the topmost level, these are specified as communications and navigation services. They are generally considered a related set because they very often rely on the same physical forms for their fulfillment (e.g., radios, antennas, etc.).

Communications services can be further specified in terms of link direction. Forward links typically refer to command (i.e., uplink) services, whereas return links typically refer to telemetry (i.e., downlink) services. And, to be even more specific, telemetry services are typically broken down into engineering telemetry, which monitors spacecraft health and status and is generally low data rate, and science telemetry, which, being the basic rationale for many missions, is typically very high data rate.

Navigation services are typically specified as the measurement of observables (i.e., data types such as Doppler and range), and also as higher level processed navigation solutions (i.e., state vectors and ephemeris files). Observables can be either Earth-ground-based or determined via localized navigation infrastructure elements, such as GPS or lunar relay satellites (Ely, 2005). Further, for specific mission phases, such as descent and ascent, certain lunar elements will also rely on inertial systems. Finally, accurate timekeeping is also generally considered a part of the suite of navigation services.

Lunar Reconnaissance Orbiter: Requirements and Current Design

Forward link requirements for the Lunar Reconnaissance Orbiter are straightforward. A 4-kbps command link at S-band will suffice. Return link requirements fall into three categories. The first is engineering telemetry. For this function, data rates of 16, 32, 64, 128, or 256 kbps will be needed at S-band using BPSK modulation of a downlink subcarrier. In addition, the mission also plans to support a 2.186-Mbps S-band QPSK link by directly modulating the downlink carrier. Second, an emergency telemetry link of 125 bps, again at S-band, will be needed. Rationales for these requirements include the desire for low costs by minimizing non-recurring engineering (NRE) and maximizing use of existing infrastructure, and being ready for a 2008 launch. Finally, a high data rate telemetry link will be needed to return the mission science data. This will require 100 Mbps at Ka-band (26 GHz) using QPSK modulation, with concatenated Reed Solomon and Rate 1/2 convolutional coding. Ideally the mission would return greater than 100 Mbps but the transfer rate is limited by onboard SpaceWire hardware. The high-rate parameters translate to a symbol rate of 229 Msps. LRO's flight telecommunications system will utilize a 5-W S-band transmitter, with either a high gain or omni-directional antenna to send the engineering or emergency telemetry data. Antenna selection will be made in flight depending upon the phase of mission operations. The high rate science data will be sent via a 20-W Ka-band transmitter through the spacecraft's high gain antenna.

An additional set of requirements involves proximity links. Because NASA's lunar planning envisions a series of missions, it is logical to deploy in situ communications and navigation capability with each orbiting asset, so as to provide support for future landed elements. However requirements for the landed elements that immediately follow LRO are not well defined. Hence, requirements on LRO are currently very minimal. Proximity links will be available, but a user element would have to transmit on LRO's uplink frequency and receive on LRO's downlink frequency. Should requirements from the follow-on missions become drivers, it may be necessary for LRO, or later orbiters, to fly Electra-class proximity radios. These radios are currently in use by NASA/JPL missions at Mars (Edwards et al., 2003). Should an international fleet of lunar missions actually occur, with cross-support agreements, as appears likely, a transition to an Electra-class proximity system would be very logical. However, it should be noted that long-term maintenance of a low-lunar orbit to provide relay services for future missions significantly increases orbiter propellant requirements.

LRO's 50-km altitude lunar polar orbit poses challenging navigation requirements. Successful execution of the prime mission phase will require that LRO's orbit be determined, at the 1-σ level, to 500 m along-track, 500 m cross-track, and 18 m radial. The very stringent requirement in the radial direction enables accurate topographical resolution, a high-priority mission science objective. A previous mission, Lunar Prospector, did achieve a radial direction navigation accuracy of 13 m, albeit from a higher orbit of 100-km altitude. The difficulty of determining orbits at the Moon traces to the lack of a high-accuracy lunar gravity field, especially on the lunar far side. Future orbiter missions to the Moon may ultimately migrate to X-band (8 GHz) or Ka-band (26 GHz) to obtain higher accuracy radiometric observables.

Robotic and Human Mission (CEV) Needs

Given the evolving nature of the lunar mission model, it is necessary to take a heuristic approach to requirements definition (Noreen et al., 2005), (Soloff, 2004). Taking account of lessons learned from robotic planetary missions is essential, such as the need for reliable communications during critical events.

Two basic types of communication links will be needed: high reliability channels and high rate channels. High reliability channels are used for operational and critical event communications that must arrive, and do so with minimal latency. Forward (Earth-to-space) high reliability links include digital commands and digitized speech (to astronauts); return (space-to-Earth) links carry digitized speech, engineering data, video (if there is sufficient bandwidth) and limited science data. High reliability channels must:

- operate over near continuous (24/7) redundant links in the vicinity of a base on the surface of the Moon or Mars;
- serve spacecraft en route to the Moon or Mars, and during descent and ascent;
- support multiple spacecraft, robots and astronauts simultaneously;
- if there are human occupants, support commands and engineering telemetry plus two-way speech and video at any time from any spacecraft attitude.

High rate forward links will be used for large command loads, high-resolution video and other high volume data, such as biomedical, scientific, and engineering information, as well as morale media (e.g., music) for astronauts. On the return link, high rate channels will support high rate science and public outreach applications like hyperspectral imaging, radar and high definition television. Reduced availability is acceptable for these high rate channels; interruptions due to adverse weather on Earth or temporary pointing problems are tolerable.

To proceed with the requirements definition, we assume a single lunar base, in a polar region, from which astronauts would not venture more than 100 km. The base communications system would support continuous redundant reliable channels and, when available, high rate channels through a steered antenna. Additional assumptions include:

- 12 astronauts at or near the base, requiring up to 6 simultaneous two-way voice channels, which can be monitored on Earth. Astronauts would use omni-directional antennas.
- 4 transports carrying humans, which would need simultaneous reliable channels supporting up to 10 kbps on the forward link and up to 1.5 Mbps on the return link for each transport through omni and steered antennas. High rate channels could be used when available.
- 24 robotic rovers simultaneously using two-way reliable links with up to 100 kbps on the forward link and up to 1.5 Mbps for video on the return link using omni and steered antennas. High rate channels could be used when available.

Communications Services (Forward and Return)

Tables 1 and 2 summarize presumed data rate requirements based on the nature of data being transferred. Table 3 shows how return link data from anticipated users add up.

TABLE 1. Forward Link Requirements

Data Type (Reliable Channel)	Data Rates	Element
Speech	10 kbps	Astronaut
Digital Channel	200 bps	Astronaut
Digital Channel	2 kbps	Transport / Rover / Base
Data Type (High Rate Channel)	**Data Rates**	**Element**
Command Loads	100 kbps	Transport / Rover / Base
CD-quality Audio	128 kbps	Astronaut
Video (TV, Videoconference)	1.5 Mbps	Astronaut

TABLE 2. Return Link Requirements

Data Type (Reliable Channel)	Data Rates	Element
Speech	10 kbps	Astronaut
Engineering Data	2 kbps	Astronaut
Engineering Data	20 kbps	Transport / Rover / Base
Video	100 kbps	Helmet Camera
Video	1.5 Mbps	Rover
Data Type (High Rate Channel)	**Data Rates**	**Element**
High Definition TV	20 Mbps	Astronaut
Hyperspectral Imaging	150 Mbps	Science Payload
Synthetic Aperture Radar	100 Mbps	Science Payload

TABLE 3. Aggregated Return Link Requirements

(Reliable Channel)				
User	**Channel Content**	**# of Channels**	**Channel Data Rate**	**Total Data Rate**
Base	Speech	6	10 kbps	10 kbps
Base	Engineering	1	100 kbps	100 kbps
Astronaut	Speech	6	10 kbps	60 kbps
Astronaut	Helmet Camera	12	100 kbps	1.2 Mbps
Astronaut	Engineering	6	20 kbps	120 kbps
Transports	Video	4	1.5 Mbps	6 Mbps
Transports	Engineering	4	20 kbps	80 kbps
Rovers	Video	24	1.5 Mbps	36 Mbps
Rovers	Engineering	24	20 kbps	480 kbps
Aggregate				**44 Mbps**
(High Rate Channel)				
User	**Channel Content**	**# of Channels**	**Channel Data Rate**	**Total Data Rate**
Base	HDTV	1	20 Mbps	20 Mbps
Transports	HDTV	1	20 Mbps	20 Mbps
Transports	Hyperspectral Imaging	1	150 Mbps	150 Mbps
Rovers	Radar	1	100 Mbps	100 Mbps
Rovers	Hyperspectral Imaging	1	150 Mbps	150 Mbps
Aggregate				**440 Mbps**

The aggregate data rate for reliable channels is 44 Mbps, dominated by simultaneous video from 24 robotic rovers (1.5 Mbps from each rover). We assume high rate channels are shared. The aggregate data rate for high rate channels is 440 Mbps. If additional high rate channels are necessary, there may be a need to support a substantially higher aggregate data rate.

Tracking and Navigation Services

Navigation will certainly be required for missions en route to the Moon and returning back to Earth. Also, navigation will be needed for descent and landing, for surface navigation, and for ascent. The trip between Earth and the Moon is navigable with known techniques that trace to the Apollo program in the 1960s. Radio-based navigation will provide Doppler and range measurements, essentially as a by-product of the routine communications link between spacecraft and Earth. What differentiates the upcoming era of human lunar exploration from the Apollo era is the need for extremely precise landing accuracy. Obviously, the establishment of a permanent lunar base will depend upon the ability to first deploy it, then staff, service and resupply it with an ongoing number of missions. Base establishment requires the ability to precisely land at a site that has been pre-determined via prior orbital remote sensing missions or robotic lander exploration activity. Once established, navigation needs to be good enough to ensure that a lander will land within easy walking distance of the base, but far enough away to ensure that the base is not damaged by the actual landing sequence of events. This is sometimes referred to as a "Go To" capability and is estimated to require on the order of 100-m accuracy.

Earth-based radiometrics (i.e., Doppler and range measurements) will certainly be used to support lunar descent, landing, and ascent. Classic 2-way coherent Doppler can ensure that the 100-m accuracy is achievable, at least at the start of the final descent sequence of events. 1-way Doppler may achieve 1 km accuracy at the same point in the arrival trajectory, though this will require the vehicle to carry a 10^{-12} s/s class ultra-stable oscillator (USO). In either case, active terminal guidance using inertial measurement units (IMU), in-situ assets, and hazard avoidance techniques will be needed to ensure that the 100-m accuracy at final touchdown is achieved.

Once a crew is safely delivered to the lunar surface and checked into the base, the focus of operations shifts from descent and landing to surface operations, introducing different navigational challenges. In the highly dynamic environment of descent and landing, navigation must provide knowledge and control of all six components of the CEV's rapidly evolving state vector. In contrast, the operation of landers and rovers on the lunar surface is much less dynamic. Knowledge and control of vehicle velocity is not critical. Position is the more relevant part of the total state vector. Further, since one element of the position vector is constrained to lie on the lunar surface, the other two components predominate. Earth-based navigation, using Doppler and range measurements, is not very useful for this type of activity. There are simply insufficient dynamics to generate a signature useful for positioning. Much more useful would be a constellation of in-situ lunar navigation satellites, akin to the Earth GPS constellation. However, the number of users on the lunar surface will be too small to justify an analogous investment. But it is reasonable to consider that a small number of such satellites will be available to support surface positioning. The goal would be to achieve a position fix in two dimensions of 10 m or better. If only one lunar orbiter is available to provide this surface positioning, between two and four passes will likely be needed to gather enough data to meet the requirement. This would obviously bring lunar surface operations to a standstill for many hours. However, two orbiters, along with a surface beacon whose position has been accurately determined by prior survey, could achieve the desired accuracy in near real-time.

Evolution to Human Exploration of Mars

There exists much precedent for robotic exploration of Mars in terms of both mission requirements and systems that can meet those requirements. Over the last decade, NASA has had a rich program of Mars exploration that has included orbiters, landers, and rovers. ESA is currently operating Mars Express at the red planet. But obviously, no such experience base exists for the human exploration of Mars. Nevertheless, it is reasonable to assume that requirements for human Mars exploration will be comparable to those of human lunar exploration. There will, of course, be differences. Mars does have an atmosphere as well as some seasonally available surface volatiles that may enable in-situ resource utilization approaches unique to that planet. It also has a rotation period that will eventually face any meridian of the planet towards Earth. And of course, it has a significantly longer round-trip light time for communications. This last factor will translate into latency and autonomy requirements different from those at the Moon. For example, the impossibility of instantaneous voice communications with Earth will likely relax some requirements on these links. On the other hand, the unavoidable light time delay will enhance the need for operational autonomy in such real time activities as rendezvous, docking, descent, and ascent.

All things considered, we would expect that the architectural forms needed for human Mars exploration may not be too different in character from their lunar analogs but will, of necessity, be scaled up many times in terms of performance. An early form of a "Planetary Area Network" is already in existence and operating daily in Mars orbit. Relay radios onboard the Mars Global Surveyor (MGS), Mars Odyssey, and Mars Express orbiters have been used to improve the science return of the two Mars Exploration Rovers by over two orders of magnitude. The Mars Reconnaissance Orbiter (MRO) has just launched and is on its way to join this fleet. It will carry the most advanced radio yet for proximity link communications. Odd as it may sound, lessons learned from this successfully operating network at Mars can be translated back to the lunar environment to enrich exploration efforts at our natural satellite.

ARCHITECTURAL FORMS

Once requirements are specified, it is possible for systems architects and designers to define the hardware, software and interfaces that will be needed to provide the required services. Typically there can be numerous choices, as shown in Table 4. Each choice comes with its own advantages and disadvantages.

TABLE 4. Candidate Forms to Follow Functions

Architectural Form	Notes
18-m monolithic 26-GHz antenna	1 antenna at White Sands Complex
34-m monolithic 26-GHz antennas	3 antennas, 1 at each of 3 DSN Complexes
DSN Demo Array	2 x 12-m S-band antennas + 4 x 12-m arrayed 26-GHz antennas at Goldstone
DSN RLEP Array	3 x 12-m S-band antennas + 6 x 12-m arrayed 26-GHz antennas / Complex
Near-Earth Array Network	6 x 18-m S-band and 26-GHz antennas at each of 3 TBD longitudes
10-m class commercial 2-GHz antennas	Capabilities and sites as available from commercial provider(s)
TDRSS	Geostationary Earth Orbit
GPS	"Middle" Earth Orbit
Lunar Nav-Com-Sat Constellation	Lunar Elliptical Orbit
Spectrum Allocation	S-band (2 GHz), X-band (8 GHz) and Ka-band (26 GHz)

The current baseline plan for LRO leverages a commercial partnership NASA utilizes for its near-Earth Ground Network. Using this arrangement, low rate S-band command and telemetry links will be provided by a commercial service provider. High rate Ka-band (26 GHz) science telemetry links will be provided via an 18-m antenna, to be installed at the NASA-owned White Sands Complex in New Mexico (see Figure 3).

FIGURE 3. GSFC 18-m Antenna

Frequency allocations make efficient use of spectrum (another physical resource) by using S-band and Ka-band where most appropriate. Looking beyond LRO, additional assets will likely be needed to support the follow-on robotic lunar exploration missions and certainly for the Crew Exploration Vehicle and other elements of the human exploration program. Installation of 26-GHz receivers on DSN 34-m antennas has been proposed. Such an antenna is shown in Figure 4.

FIGURE 4. DSN 34-m Antenna

The larger apertures would provide enhanced data rates and link margins and the global distribution of assets would enable continuous coverage. Other possibilities under serious consideration forego monolithic antennas in favor of array-based approaches. An initial implementation of a DSN Demonstration Array at NASA's Goldstone Complex has been proposed. It would comprise four 12-m arrayed antennas that would receive high rate science telemetry at 26 GHz along with two 12-m S-band antennas for lower rate forward and return links. This demo facility may grow into a DSN Robotic Lunar Exploration Program (RLEP) array comprising six arrayed 26-GHz antennas along with three S-band antennas at each of the three DSN complexes for continuous coverage. Another proposed approach would evolve the 18-m antenna at White Sands into a Near-Earth Array Network of six 18-m antennas, each with S-band and 26 GHz, at each of three longitudes, for support of LaGrange Point as well as lunar missions. A depiction of such an antenna array is provided in Figure 5.

The first destination for the CEV has been identified as the International Space Station. It will by necessity be supported by NASA's constellation of TDRSS satellites. Likewise, the US Air Force GPS satellite constellation will be used to provide navigation data for the CEV while operating in low Earth orbit, departing to or returning from the Moon. Operations at the Moon, whether robotic or human, are likely to be supported by an in situ system of navigation-communications satellites in lunar orbit. This is particularly important for coverage of the lunar polar regions, which are prime areas of interest, or the lunar far side. Between 3 and 6 such satellites will probably be needed depending upon whether partial or full lunar coverage is the ultimate requirement. Figure 6 depicts a notional view of such a 3-satellite constellation.

It would be inappropriate to end this section without some mention of optical communications. For some time now, NASA has had a significant research effort in this area. Until very recently, this effort appeared to be coming to fruition as the Mars Laser Communications Demonstration (MLCD) on the Mars Telecommunications Orbiter (MTO). MTO was slated for a 2009 launch, not only to provide proximity link support for NASA's 2009 Mars Science Laboratory (MSL) rover, but also to deposit enduring communications infrastructure in Martian orbit for the benefit of future missions. Because MTO was primarily to be a comsat, rather than a science orbiter, it also was to serve as a demonstration platform for the very first deep space optical communications link. However, recent policy and budgetary factors have shifted near-term program priorities less towards Mars and more towards the Moon. As a result, MTO has been indefinitely deferred, and along with it the MLCD payload. Nevertheless, much optical communications technology was developed under this program and is now available for use at the Moon as well as eventually at Mars. No decisions have yet been made to implement optical communications capabilities for the lunar exploration program, but the technology is a natural one to consider for its very high performance level, unconstrained bandwidth potential, and eventual applications at Mars.

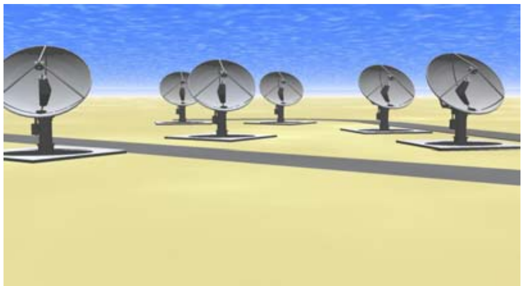

FIGURE 5. DSN Robotic Lunar Exploration Program Array

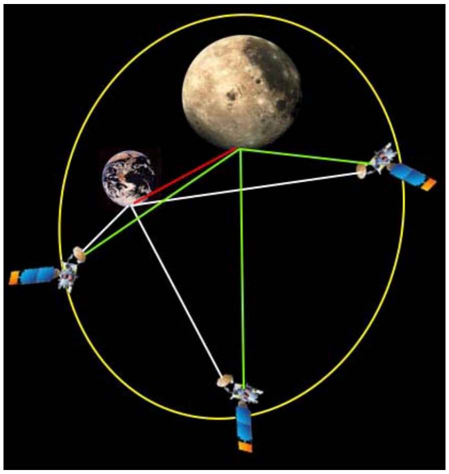

FIGURE 6. In Situ Lunar Communications and Navigation Constellation

ARCHITECTURAL INTERFACES

So far we have considered the architectural functions and architectural forms required for lunar mission support and made note of the classic principle of "form follows function." However, there is a third element generally considered to be part of a system architect's tool kit: the interface structure. Or more colloquially, how do all these various and sundry parts play together to yield the desired functionality? Appropriate partitioning of forms and allocation of interfaces enables the services to be provided to customers in a reliable and efficient manner. An inappropriate interface structure can result in a total system that is difficult for a customer to access and unwieldy for a service provider to manage.

Here again, there are choices for the architect. Because of the relatively large number of forms that can be used to deliver the set of services, all of which involve communications, it is clear that a networking approach is needed. Networking then raises issues of data routing and standards, in the regimes of both space-to-Earth and space-to-space. The Consultative Committee on Space Data Systems (CCSDS), which numbers the world's major space agencies among its members, has done extensive work, over many years, to define, research and codify standards for such communications. These standards facilitate the transference of data across the space-to-space links, space-to-Earth links and even the extensions all the way to the various Project Operations Control Centers. CCSDS recommendations are easily obtainable from the organization's web site (CCSDS, 2005). Use of standards permits the needed services to be delivered across the networked architecture in the most effective and efficient manner. Standards even allow for differing levels, or qualities of service delivery. Finally the subjects of operability, and of course interoperability, again between space and Earth as well as space-to-space must be considered. ESA's network of tracking antennas and NASA's DSN, in particular, have incorporated CCSDS standards and as a result have enjoyed significant benefits in terms of cross-support and interoperability.

Within the NASA community, there is an emerging understanding that space data communications should move towards a networked model of operations. Whereas a recent article (Jackson, 2005) may have left an impression that significant polarization exists within NASA over issues relating to networking, the reality is somewhat different. In fact, a growing consensus envisions the need to combine several powerful new space data communications techniques if a Solar System Wide Area Network is ever to be achieved. For example, there is no disagreement that the terrestrial Internet's TCP/IP protocols can be extended to embrace some space applications. Doing so would leverage the huge financial investment that has already been made in software for the terrestrial Internet as well as benefit from the experience of the millions of “beta testers” who log on every day. However, TCP/IP was created to support data transfer across a constantly connected, near real time network, such as we all enjoy here on Earth. But TCP/IP will face difficulties in a spatial regime where network connections are made and broken episodically and where communications delay times become significant, owing to the finite speed of light. And these are exactly the kinds of communications links that will characterize at least the early stages of lunar exploration, and certainly forays into more distant realms. The Moon is of course fairly close to the Earth. Nevertheless, Moon-to-Earth links will suffer a noticeable communications lag time along with a high probability that end-to-end communications paths may not be continuously sustainable. Whether the lag will prove amenable to TCP/IP is a subject of current investigation. But what is clear is that the making and breaking of links to lunar locations out of direct line of sight to Earth, however transient, will almost certainly require a networking approach that is tolerant of significant disruptions. Thus the overlay of a Disruption Tolerant Networking (DTN) protocol suite on top of—or even, in some circumstances, replacing—a conventional TCP/IP approach will be needed. Networking the Solar System will require the merger of at least two, and possibly even more, data communications technologies. Taken together, these approaches will allow space communications architects to effectively accommodate episodic connectivity, unidirectional communications, network disconnection, and significant round trip light times that will routinely be encountered in voyages to the Moon, Mars, Europa, Titan, or anywhere else.

OPPORTUNITIES FOR INTERNATIONAL COLLABORATION

As we have seen earlier, there is a great rekindling of interest in lunar exploration and plans for a sizeable international fleet of spacecraft to pursue that interest. This will of course lead to challenges and opportunities in the areas of communications, navigation, and mission operations. One obvious challenge is the sharing of limited spectrum. Another is the wide variety of techniques that can be selected to provide the needed functions. Significant opportunities exist in the area of cross-support. The lunar-bound or lunar-based assets of any one entity may be able to obtain their needed architectural functions from the architectural forms of any of the other entities engaged in the exploration effort. Achieving this goal does require more implementation of standardized approaches to service provision, which of necessity entails less utilization of proprietary techniques. There are always trade-offs among these competing alternatives, but it is felt most exploring entities consider that the benefits of standardized approaches do outweigh any perceived disadvantages.

A good example of such cross-support would be the use of relay radios on one entity’s lunar orbiters to support the landed assets of another. To achieve such interoperability does not require that each entity use the exact same equipment, but only that the general techniques be compatible and the necessary interfaces be standardized. Along these lines, it is noted that international communication collaborations have already proven very useful at Mars. Looking out a little further, one can easily envision an international lunar network that operates for the benefit of all. These benefits may offer better protection for the lives of the valiant lunar explorers in addition to enhanced mission science return.

CONCLUSIONS

This paper has tried to apply the perspective of systems architecting in the area of lunar mission support: form does follow function, and; interfaces do matter. NASA’s lunar exploration program is beginning to take shape. The same can be said for space agencies of other nations as well as for commercial enterprises. ESA’s SMART-1 is currently operational at the Moon. Requirements for communications and navigation services are being defined. Candidate architectural forms that can satisfy these requirements are either already in existence or are on the drawing boards of architects and designers. Standards are in place or being developed to manage the resulting interfaces. Many players across this Earth, both governmental and commercial, will be involved. Working together, we can accomplish much.

Though the final systems to be emplaced cannot be fully described just yet, there is no doubt that a rich set of options exist within our technological reach. As lunar programs proceed, it will be exciting to watch and participate in the development of systems that will enable success of these ventures and a bountiful harvest of exploration results.

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